N74-10234

Paper No. 2

A THERMAL VACUUM TEST OF SKYLAB ORBITAL WORKSHOP REFRIGERATION SUBSYSTEM

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ABSTRACT

This paper describes the facilities, test support equipment, and test setup of a thermal qualification test performed on a fully operational Refrigeration Subsystem (RSS). This subsystem consists of a radiator, radiator thermal control unit, pump assembly, wardroom freezer, food freezer, urine freezer, urine chiller (simulated), water chiller, and electrical cold plate. These components and the connecting plumbing comprise one complete coolant loop of the refrigeration system thermally and is functionally equivalent to the flight system. Coolant is circulated through freezers and chillers accepting heat for rejection to space by radiation. Design features and thermal operating characteristics of the test specimen are discussed. Results are presented on radiator heat rejection performance, radiator/thermal capacitor integrated thermal performance, coolant temperature control and temperature control hardware, coolant pumping equipment, regenerative chilling equipment, freezers, chillers, etc. Redundancy features of the flight system are also discussed.

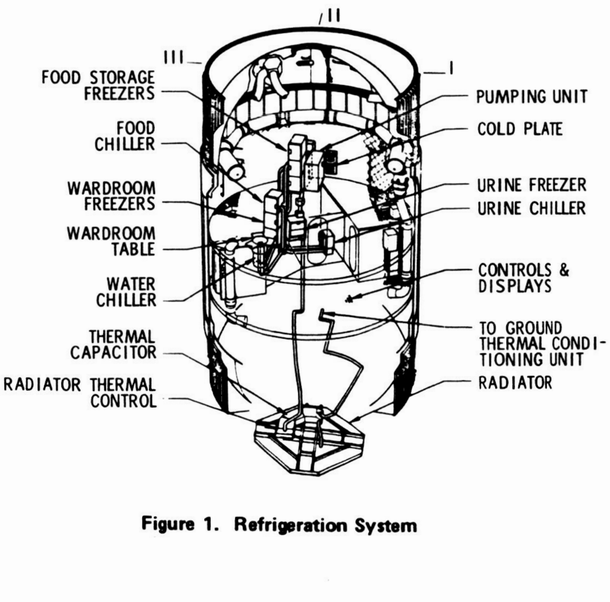

Figure 1. Refrigeration System

System Description

Frozen food, refrigerated food and water and freezing and chilling capability for medical experiments was provided aboard the Skylab vehicle by a circulating coolant refrigeration system (See Figure 1). Low temperature single phase coolant (Coolanol-15) passed through insulated freezer and chiller compartments accepting heat for rejection to space by radiation. The system is required to operate in two temperature ranges, 0°F to -20°F for freezers and +35°F to +45°F for chillers.

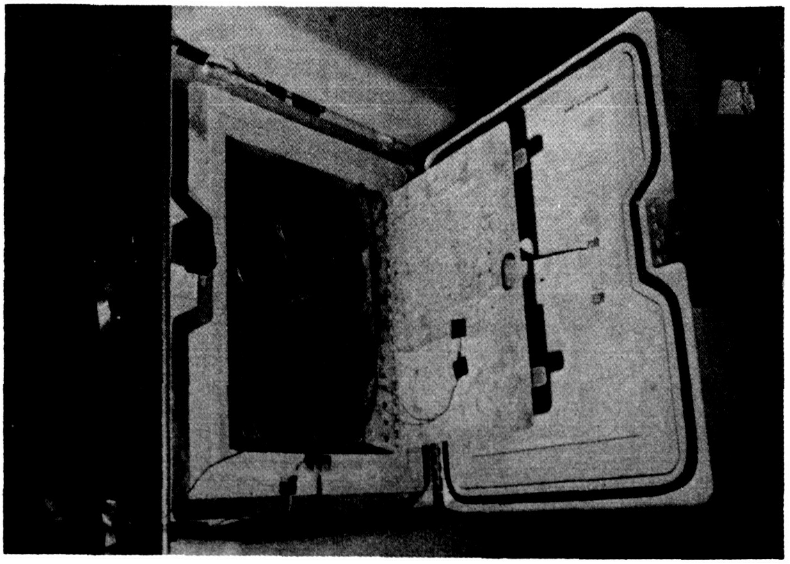

Figure 2. Food Compartment

Food was maintained in a frozen state in two freezer units, the wardroom freezer and in the food storage freezer. The freezers were located inside the spacecraft crew quarters. Each freezer is a rectangular container 21 in. x 21 in. x 76 in. high with an internal storage volume of 6 ft^3 in three equal size cubical compartments. Full face mechanically latching doors with perimeter seals provide maximum access to each compartment. Freezer cooling is achieved by flowing low temperature heat transfer fluid through aluminum tube-plate (dip brazed) heat exchangers which make up the compartment walls. Compartments are insulated from the outer aluminum structure and each other with polyurethane foam insulation. The top compartment of the wardroom freezer was utilized as a chiller where temperatures were maintained from +35°F to +45°F. Frozen food was provided in circular pop top cans stored in cylindrical canisters. The canisters were placed in a rack inside the freezer compartment. (See Figure 2).

A medical experiment freezer for freezing urine and blood samples was a single compartment unit similar in construction to the food freezers but much smaller in size. This unit contained trays into which urine and blood samples from the spacecraft crew were frozen. These samples were eventually returned from orbit for medical analysis. The sample trays included a phase change material heat sink to maintain low temperature during deorbit from the time the trays were removed from the medical experiment freezer in orbit until they were placed into an earthbound freezer on the recovery vessel. (See Figure 3 - Urine trays and samples.)

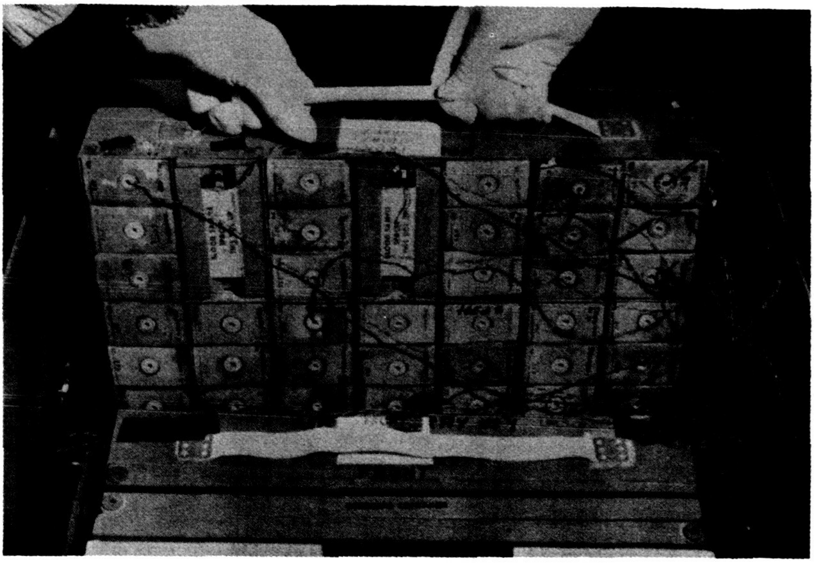

Figure 3. Urine Trays and Samples

Chilled water was provided by passing water through an insulated coiled tube heat exchanger to either a hand-held drinking dispenser or a table mount dispenser for reconstituting foods.

Rejection of system heat load and coolant temperature control were accomplished with the space radiator and the low temperature thermal control equipment located on the aft end of the spacecraft. The radiator is a flat octagonal shaped tube-fin heat exchanger with an effective heat exchange area of approximately 85 square feet. Radiator coolant extrusions are seam-welded to the radiating surface. The radiating surface is finished with a high emissivity low absorbtion coating. Polyurethane foam insulation, reflective surfaces and glass felt insulation on the radiator back surface minimize heat flow in this region.

During a typical earth orbit cycle, radiator outlet coolant temperature can vary as much as 60°F. A thermal control unit adjacent to the radiator, controlled and modulated radiator outlet coolant to minimize temperature excursions of the fluid delivered to the freezers.

A coolant temperature modulating device within the thermal control panel called a thermal capacitor 'rectifies' radiator outlet coolant temperature by storing and releasing thermal energy at the heat of fusion point of a phase change material (PCM). The thermal capacitor is a plate-fin coolant coldplate with honeycomb tanks of PCM bonded to either face. The thermal rectification mode of control provides exclusive temperature control when the radiator is operating in a warm or moderate heat rejection environment. For colder radiator operation, the thermal capacitor remains mostly frozen and coolant outlet temperatures can be quite low. For this mode coolant flow is periodically directed to bypass the radiator on a path directly to the thermal capacitor to continue the freezing and thawing cycle in the capacitor. Bypass control is accomplished automatically with an electronic controller and temperature sensors at the thermal capacitor. The temperature sensors provide the positioning command to a solenoid operated two-position valve. Temperature sensors on the radiator surface can also divert flow to bypass in the event of a too warm radiator surface. A relief valve is included across the radiator in the event the coolant freezes in the radiator.

Coolant pumping and chilling equipment is located inside a container in the spacecraft. The interior of the container is vented to vacuum to improve insulation performance and to eliminate the possibility of coolant leaking into the cabin in the event of a leak. Four electric driven gear pumps are included in a single coolant circuit. Only one pump is operated at any one time. The operational time span of each of the four pumps is programmed to allow for the long duration mission. Two independent refrigeration coolant loops are provided onboard the Skylab, a primary system and an alternate backup. Both systems are identical. Loop switching if required may be accomplished manually or automatically, either by the spacecraft crew or from the ground according to various performance parameter fault indications, freezer hi-temperature indication, chiller low temp indication, accumulator low level indication, low pressure indication (causes pump switching in sequence and eventual loop switching).

Temperature operation in the $+35^{\circ}F$ to $+45^{\circ}F$ range was achieved with regenerative heat exchangers and a temperature regulated mixing valve set to operate from $+36^{\circ}F$ to $+42^{\circ}F$. An electric heater was included in the chiller circuit to prevent low temperature freezeup in the water chiller. The heater functions automatically according to commands from an electronic controller and temperature sensors in the regenerative circuit.

Refrigeration piping was stainless steel seamless tubing. All joints were electro-brazed except for interfaces with major components which were standard boss fittings. Elastomer seals were used in non-vacuum application where temperatures were above $0^{\circ}F$. Metallic K seals were used for low temperature vacuum applications. The relatively low volume accumulators 106 cubic inches in relation to the total system volume of 900 cubic inches necessitated a leak-tight system. The above piping and joint arrangement provided the desired low leakage characteristics. Piping was insulated with cylindrical polyurethane foam insulation sections sheathed in aluminum for fire protection. Insulation segments were clamped together and joints sealed with tape.

Operation of the Skylab Orbital Work Shop Refrigeration System begins several weeks before launch. The system is activated and chilled down and maintained cold with a water-glycol ground thermal conditioning unit. Frozen food is placed into the freezers. The spacecraft is checked out and sealed off in preparation for launch. Refrigeration system pumps are turned off during boost into orbit. Once in orbit, the radiator assumes the heat rejection job and the system operates continuously throughout Skylab mission. A summary of Refrigeration System design and performance characteristics is given in Table 1.

Table I. REFRIGERATION SYSTEM DESIGN & PERFORMANCE CHARACTERISTICS

Coolant -- Coolanol-15
Total system coolant volume (one loop) -- 900 in^3
Total maximum accumulator volume (one loop) -- 106 in^3
Coolant operating pressure range -- 18 to 118 psia
Coolant flow rate -- 125 lb/hr
Maximum prelaunch heat load -- 1700 BTUh
Maximum orbital heat load -- 1300 BTUh
Minimum orbital heat load -- 750 BTUh
Food freezers operating temperature range -- $0^{\circ}F$ to $-20^{\circ}F$
Urine freezer operating temperature range -- $-2.5^{\circ}F$ to $-34^{\circ}F$
Chillers operating temperature range -- $+35^{\circ}F$ to $+45^{\circ}F$
Radiator heat rejection at maximum conditions -- 1500 BTUh
Thermal capacitor heat of fusion at $-14^{\circ}F$ -- 1800 BTU
Approximate system operating life -- 9000 hrs
Designated operating life of one pump -- 2250 hrs

Test Facility

To test a subsystem of such magnitude, requires a facility that has two adjoining chambers, one of which is capable of simulating cold black space and pressure below 1×10^{-6} Torr and the other capable of duplicating the Skylab cabin environment. The McDonnell Douglas Space Simulation Laboratory's 39-foot chamber and adjoining manlock were used for this test. (See photograph Figure 4.) Four of the components and the interconnecting plumbing of the RSS were installed in the spherical 39-foot chamber. These were the radiator, radiator thermal control assembly, pump and chiller assembly, and radiator

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bypass valve controller. The balance of the RSS system, such as the urine freezer, wardroom freezer, food storage freezer, water chiller, urine chiller (simulated) and electrical cold plate, were installed in the manlock chamber. (See Figure 5 - Test Setup Schematic). The manlock chamber is approximately 10 feet in diameter and 13 feet long, equipped with a separate pumping system so that the pressure in the manlock chamber is independent of that in the 39-foot chamber. Provision also was made to allow this chamber to be pressurized up to 26 psia for simulating the Skylab prelaunch cabin pressure. An aluminum tube/plate extrusion type black thermal shroud was built for the manlock chamber to provide the required Skylab cabin environment temperature. A thermal control cart circulated freon in the shroud to control and maintain a stable temperature.

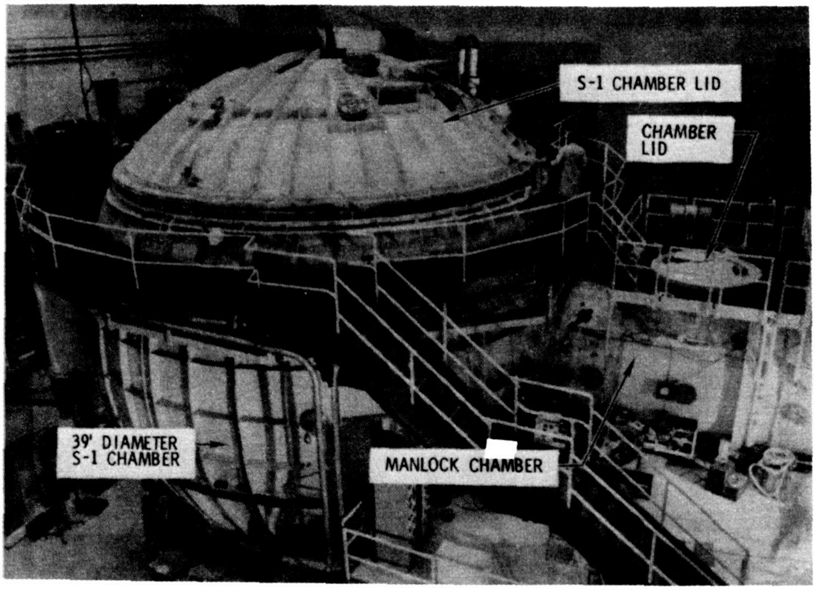

Figure 4. 39-Foot Diameter Space Simulator and Manlock Chamber

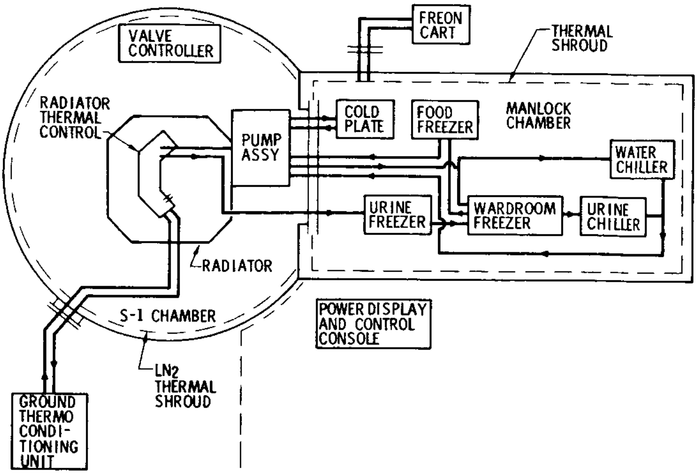

Figure 5. Test Setup Schematic

Test Support Equipment

A modified NASA Model S14-121 Thermal Conditioning Unit, similar to the unit used at the Skylab launch site, was used to provide the refrigeration system initial thermal conditioning (childown) and continuous thermal control during the prelaunch interval. Also, a separate refrigeration system service cart was used to perform four basic functions: It evacuated the coolant loop, filled and drained coolant, circulated and flushed the coolant in the system and reduced the air and moisture content of the coolant.

The power, control and display panel was built for proper RSS operation and performance display. Electrical power to the RSS was applied and controlled through this panel. The display parameters were provided for immediate readout to determine the RSS current performance status which allowed quick and accurate monitoring of the system.

To provide the radiant heat flux for the test, an Infrared (IR) Lamp Array was assembled with line reflectors containing twenty 500W quartz lamps each. To cover the approximately 10-foot-square area of the radiator surface, seven lines of these reflectors were used, spaced at 20 inches. The plane of the IR Array was placed 24 inches above the radiator surface. (See Figure 6 - IR Lamp Array and radiator surface.) This array was capable of providing an incident flux of up to 1.4 solar constants at rated voltage. In order to reduce the background effect, the individual reflector lines were cooled with liquid nitrogen and the reflector bodies painted with 3M Black Velvet paint. The IR lamp array was calibrated and the uniformity determined. Analysis of the flux readings showed that 80% were within ±5% of the average flux for the field, and 98% were within ±10%. An ignitron power supply, Thermac Controller and Data Trak programmer and a feedback radiometer were used in a closed control loop to simulate the orbital heat flux cycles. The desired heat flux curve was fed into the Data Trak program chart which rotates at a rate equivalent to the Skylab orbital period. This curve defines the power level supplied to the IR lamp array by the ignitron which in turn is controlled by the Thermal Controller. The Thermal Controller compares the feedback signal from the control radiometer and the Data Trak output to regulate the ignitron power supply.

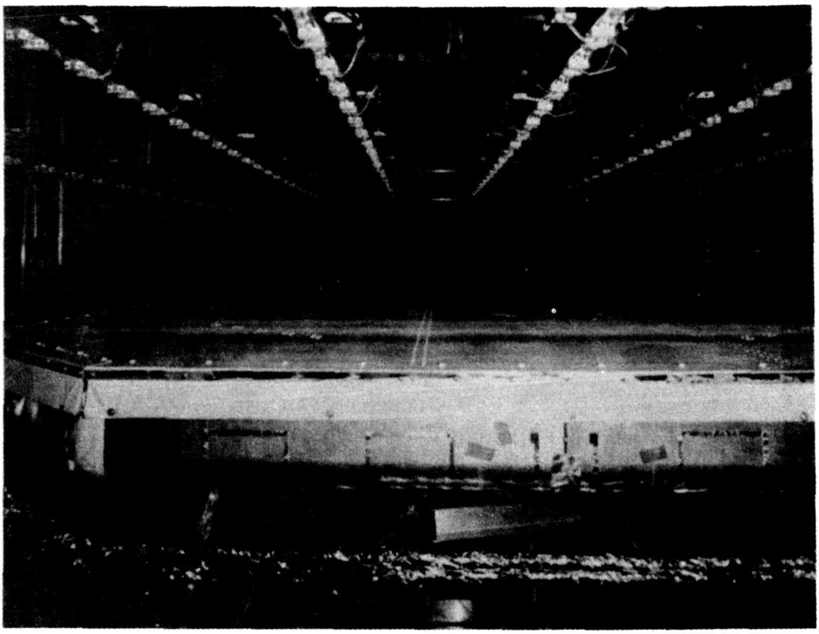

Figure 6. IR Lamp Array and Radiator Surface

Test Specimen Instrumentation

Temperature instrumentation included copper-constantan immersion thermocouples, copper-constantan surface patch thermocouples, and thermistor patches. Differential temperature measurements were obtained with three couple copper-constantan thermopiles. Pressure and differential pressure measurements were obtained with Statham Model PA 822, PL 822 and PL 872 transducers. Flow measurements were made with turbine-type flowmeters.

To measure the heat flux, three high output radiometers, Hy-Cal Engineering Model R-8410-E-01-120, were placed at the cutoff corners of the radiator. The radiometer's sensitive surface was painted with the same coating as used on the radiator surface so that the radiometers would measure the flux that was absorbed by the radiator. One radiometer was used as a feedback as mentioned above for the Data Trak Controller to control the programmed flux. Two radiometers were used for data. The radiometers were cooled by flowing 70°F water through the radiometer cooling tubes. The temperature of each radiometer was measured by a thermocouple imbedded in the radiometer body.

Key measurements were redundantly instrumented. One set was wired to the power, control and display panel where readouts were obtained by digital temperature indicators, pressure gages and light indicators. The others were scanned by the automatic data system.

Data System

Primary data for this test were acquired using a 200-channel HP-Dymec 2010J Data System having a resolution of one microvolt. Data channels were scanned using a crossbar scanner, digitized at a rate of approximately five readings per second by a five-digit integrating digital voltmeter and recorded on an incremental magnetic tape recorder for subsequent post test processing. A printer was used as required to monitor raw data values. At the start of each test, a uniform set of standardizations were recorded to verify the bias and sensitivity of each channel that used signal conditioning external to the data system, such as bridge-type transducers and turbine flowmeters. The on-line computer was programmed to initiate each scan at a specified interval. A local timer was also connected to initiate a scan in the event one was not initiated by the computer within a maximum allowable interval. Data was reduced both on-line and off-line.

The Dymec Acquisition System was coupled to an XDS-930 computer which accepts raw data and outputs calibrated data in engineering units for selected channels to the remote typewriter located at the test site. Reduced data values from a maximum of 56 channels can be typed in groups of eight channels on the remote typer. The XDS-930 program provides for updating the channels in each group and also allows the teletype operator to select which of the groups are to be typed out. The type-out occurs after each time slice of data. Also located at the test site was a Tektronix 611 Scope Display upon which two types of plotted data were available: a) a time history multiple plot previously reduced time slices from 1 to 5 data channels, b) a continuous update multiple plot of current time slices from 1 to 5 channels.

A hardcopy unit attached to the 611 Scope allowed the operator to make a hard copy of all on-line plots for immediate reference and comparison purposes.

Reduced data, besides being output to the remote typewriter and scope, was being stored on magnetic tape in the Data Reduction Facility. This calibrated data tape was used to obtain all off-line plots.

In the event of an XDS-930 Computer failure while on-line, data can be removed by processing data in an off-line mode. In this case, the Dymec raw data tape can be processed to obtain test data plots.

Test Specimen Performance

Most of the simulated orbital testing was done at maximum cabin environmental temperatures with the radiator operating in the highest absorbed energy flux environment. These conditions established the upper limits of system operation. Tests were also conducted at intermediate and coldest environment and radiator absorbed energy flux conditions to verify temperature control for all operating situations. Refer to Figure 7 for maximum and minimum net lamp flux curves.

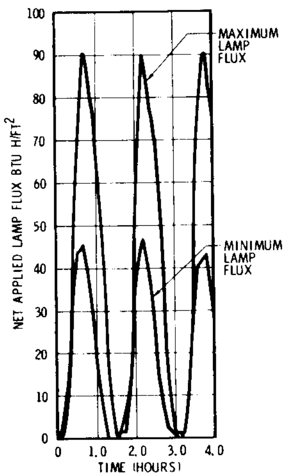

Figure 7. Net Applied Orbital Lamp Flux

Heat loads rejected by the radiator for simulated orbital conditions ranged from 750 BTU minimum to 1300 BTU maximum which corresponded to internal environment temperatures from +40°F to +79°F. For the warmest conditions radiator outlet coolant temperature ranged from +3°F to -38°F for an orbital cycle. For the coldest radiator rejection environment, the lowest recorded radiator outlet temperature was -95°F.

Thermal capacitor 'thermal rectification' provided coolant temperature control for the maximum operating conditions. Refer to Figure 8. Coolant delivered to the freezers is at constant temperature for this condition near the fusion point of the PCM. For colder operation, bypass switching resulted in the temperature control of Figure 9. Coolant delivery temperature to the freezers for this condition varied by the amount of the temperature switching limits. This variation is considered acceptable.

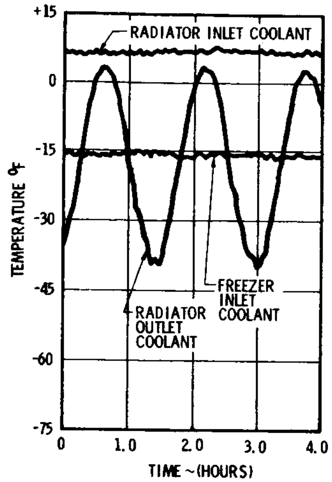

Figure 8. High Heat Load (Maximum) Operating Condition

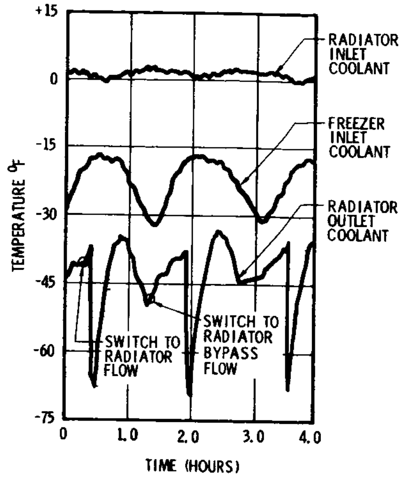

Figure 9. Low Heat Load (Minimum) Operating Conditions

Frozen food was maintained from -3°F to -20°F through the range of operating conditions. With such low temperatures there was concern early in the test program with regard to the amount of ice and frost buildup in and around the freezer doors and food cans. Since there was no provisions for freezer defrosting and the Skylab mission spanned approximately 9 months, it was felt that this could be a potential problem. Frost tests were conducted where temperature, dewpoint and ventilation conditions at the freezer doors were simulated in conjunction with door opening and food can removal operations. Considerable frost and ice buildup did occur during these tests; however, it was relatively soft in consistency and because of the low cooling capacity of the system sufficient heat was added to the affected areas when the freezer doors were opened to further soften the ice for easy removal.

DISCUSSION

The space chamber quartz IR lamp thermal simulation proved to be a good representation of the radiators earth orbit thermal environment. Radiator heat rejection and temperature characteristics were as predicted for the applied conditions. The applied orbital average net heat flux was always within 2 BTUh/Ft^2 of the required value. The automatic cycle variation of lamp intensity provided excellent transient environment simulation to permit verification of refrigeration system coolant temperature control modes.

Subsequent Skylab flight data confirmed refrigeration system operation as first demonstrated in the simulation tests. As would be expected, the Skylab refrigeration system reflected slightly more thermal performance capability than was demonstrated during the conservative simulation tests. During the first few days of Skylab operation when internal environment temperatures were as high as $+125^{\circ}F$, corresponding maximum food freezer temperatures were $+5^{\circ}F$. As Skylab internal temperatures returned to normal maximum frozen food temperatures dropped to values lower than $-5^{\circ}F$.